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Indexing Western Spruce Budworm Activity Through Radial Increment Analysis

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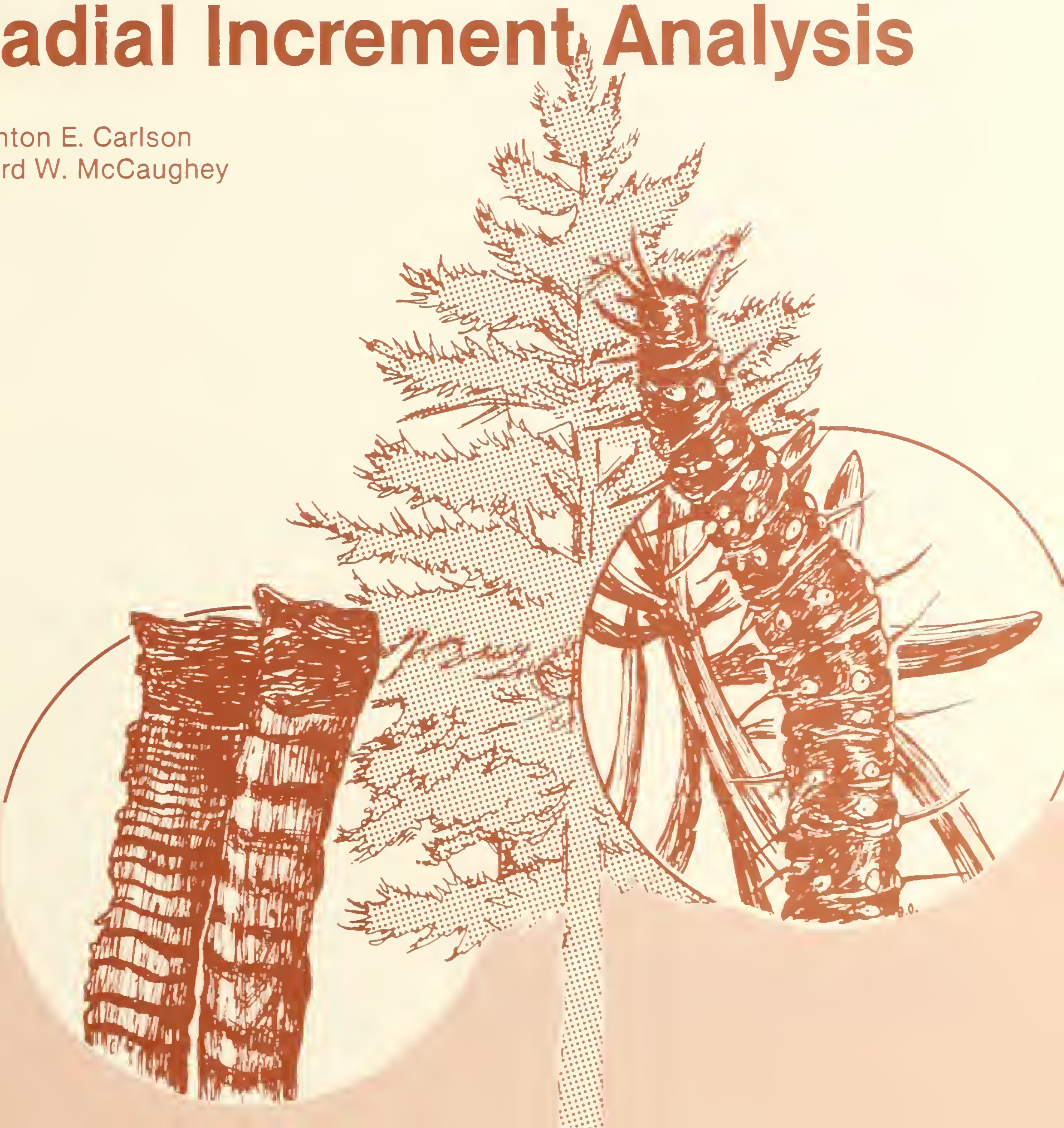

THE AUTHORS

CLINTON E. CARLSON is research forester in the Silviculture of Northern Rocky Mountain Subalpine Forest Ecosystems research work unit in Missoula, Mont. He received a B.S. degree in forest science in 1964 and an M.S. degree in forestry in 1966, both from the University of Montana. He was awarded a Ph.D. degree in botany from the University of Montana in 1978. He currently is responsible for research concerning silvicultural methods of reducing impact of western spruce budworm in the Intermountain area. Prior to this assignment in 1979, he was plant pathologist with the Northern Region, USDA Forest Service, where he conducted field studies on the effects of air pollutants on forests.

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ACKNOWLEDGMENTS

We appreciate very much the help of our field assistants, Gerald McCarthy and M. Rande Kerr, for their conscientious work in the course of this investigation. Thanks to Bryan Owen for help with the illustrations.

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RESEARCH SUMMARY

Past western spruce budworm (WSBW) activity in western Montana Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests was assessed through radial increment analyses of cores extracted at diameter breast height. A growth function, defined as the cumulative sum of squared mean annual radial increment, was graphically compared between WSBW host (Douglas-fir) and nonhost (ponderosa pine [*Pinus ponderosa* Laws.]) trees. Negative inflections of host radial growth curves relative to nonhost indicated WSBW activity; these inflections were quantified and transformed to a severity index that represents the intensity of the WSBW activity. A hazard index that may reflect effects of WSBW on establishment of natural regeneration is proposed and may be suitable for analyses relating WSBW activity to regeneration probability. Acceleration of nonhost ponderosa pine radial growth during WSBW activity in mixed Douglas-fir stands was observed.

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INTRODUCTION

Research concerning influences of western spruce budworm (WSBW), *Choristoneura occidentalis* Freeman, on conifer regeneration establishment and growth is dependent upon valid estimates of the periodicity and intensity of past budworm activity. Because aerial survey records of WSBW infestations maintained by the Forest Service lack the resolution needed at the stand level, and because direct estimates of defoliation apply only to the most recent 3 or 4 years, past WSBW activity may be best assessed by examining the radial incremental growth of surviving trees. This approach was used by Blais (1954, 1958, 1962, 1964) and by Mott and others (1957) in balsam fir (*Abies balsamea* [L.] Mill.) forests in the eastern United States, and by Williams (1967) in grand fir (*A. grandis* [Dougl.] Forbes)-Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in the West; however, procedural details varied between investigators.

Although all of the preceding studies demonstrated that past spruce budworm activity could be dated by incremental analysis, no methods of inferring intensity were given. Research concerning the influence of WSBW on establishment and growth of conifer regeneration following harvest cuts depends on an estimate not only of when WSBW activity occurred, but also a measure of the intensity and potential hazard to the regeneration process. Our hypothesis is that Douglas-fir (host) and ponderosa pine (*Pinus ponderosa* Laws.) (nonhost) within an uncut stand have similar radial growth patterns in the absence of WSBW defoliation. Because past WSBW activity would cause different radial growth patterns, the period of activity can be detected and measured. This paper describes a method to estimate the occurrence, intensity, and potential hazard of past WSBW infestations in Douglas-fir forests of western Montana. The terms outbreak, infestation, or activity mean that WSBW feeding was intensive enough to have caused an observable effect on radial growth of host trees within a stand.

METHODS

Collection and Measurement of Cores

Increment cores were collected from trees at 50 locations in western Montana during 1979 (fig. 1). Of these locations, 46 were coincident with a random selection of various harvest cuts in the Douglas-fir climax series; habitat types (Pfister and others 1977) were determined for each stand. History of WSBW was not known in these areas. The other four locations were purposely selected as baseline to test our hypothesis that radial growth pattern of Douglas-fir known to have been previously infested by WSBW is different from that of ponderosa pine at the same location. Two of these stands (156 and 158) had been heavily defoliated since 1960 and two (157 and 159) had no previous record of WSBW activity.[1] Habitat type of these four baseline stands was *Pseudotsuga menziesii/Physocarpus malvaceus*; among them slope, aspect, and elevation were similar; mean annual precipitation and other site variables were assumed to be similar.

Trees sampled for cores were selected from the uncut stands adjacent to harvested stands and were always at least 66 ft (20 m) from the stand boundary to minimize growth response to cutting. Three to four WSBW host/nonhost tree pairs were selected at each site; to minimize stand density effects, they were required to be dominant or codominant, live, and similar in diameter. If WSBW were present in the stand at the time of sample tree selection, then the most obviously defoliated host trees were chosen; it was assumed that these trees would be the best records of past WSBW activity. Diameter breast height (d.b.h., inches), height (feet),

[1] Steve Hagland, Bureau of Indian Affiars, Ronan, Mont., provided information on stand 156; Dr. David Fellin, Forestry Sciences Laboratory USDA Forest Service, Missoula, Mont., was knowledgeable about stand 158. Perusal of records maintained by Forest Pest Management, Region 1 USDA Forest Service, showed the lack of WSBW activity since 1950 over a broad area that included stands 157 and 159.

Figure 1.—Locations where increment core collections were made.

crown class, and percent live crown were measured on each sample tree (USDA Forest Service 1978).

Two 0.197-inch (5-mm) diameter increment cores were extracted at d.b.h. from opposite sides of each sample tree parallel to the topographic contour. Cores were inserted in labeled plastic straws that were thermically sealed to prevent moisture loss, returned to our laboratory, and kept frozen until measured.

Using a Bannister Incremental Measuring Machine, annual increment was cross-dated (Fritts 1976) and measured in millimeters (0.01 mm accuracy) on each core for the period 1956-78. Current increment was not measured because cores were collected throughout the 1979 growing season.

Data Analysis of Baseline Locations

Radial Growth and Precipitation

In the absence of WSBW, radial growth of Douglas-fir should be similar to that of ponderosa pine at the same location, and both should vary directly with precipitation. To test this supposition, mean incremental growth of Douglas-fir and ponderosa pine within each of the four baseline stands was plotted against time and compared to seasonal precipitation[2] as recorded at the Lubrecht site (Steele 1979). Julian and Fritts (1968) showed that a single weather station can relate to ring widths of trees 20 or more miles (32 or more km) distant. Because these four stands were within 30 miles (48 km) of the Lubrecht Experimental Forest, Lubrecht weather data were assumed to represent these sites.

Statistically, radial growth of Douglas-fir not affected by WSBW should be predictable by ponderosa pine radial growth. To test this concept, Douglas-fir radial growth was regressed year-by-year against radial increment of ponderosa pine separately for the locations with and without WSBW history. Regressions were compared within and between the locations.

Cumulative Growth Function

To enhance graphical comparison of Douglas-fir radial growth with that of ponderosa pine, mean radial incremental growth was computed by species within location and a cumulative growth function (CGF) was developed:

let $g_{56}, g_{57}, \ldots g_{78}$ = mean incremental growth of a species for 1956, 1957, . . . 1978. Cumulative growth for 1960 was defined as: $G_{cum\,60} = g_{56}^2 + g_{57}^2 + g_{58}^2 + g_{59}^2 + g_{60}^2$.

This was done for each year of increment between 1956 and 1978 inclusive, and the resultant numbers were graphed against time. The base year was always 1956. Host and nonhost data for each location then were plotted separately on the same graph.

Severity Index

To estimate the relative intensity of past WSBW activity, the assumed "normal" slope of the host curve was subjectively extended past the WSBW-induced inflection, and the ratio of actual/potential (A/P) CGF near the end of the outbreak was calculated. An index of outbreak intensity is 1-A/P in that it reflects how much more the host trees should have grown in the absence of WSBW; this value is termed "severity index" and is bounded by 1 and 0, with 1 indicating severest impact.

Data Analysis of Random Locations

Cumulative growth functions were computed and interpreted and severity indices were calculated for WSBW activity in each of the 46 randomly selected locations. As a standard we interpreted that past WSBW activity occurred when the Douglas-fir CGF curve diverged negatively (downward) from that of ponderosa pine consecutively for a period of 3 or more years.

Hazard Index

A WSBW outbreak does not necessarily represent a high hazard to the probability of securing natural host conifer regeneration following a harvest cut unless the outbreak overlaps the 10-year period immediately following the cut. During this time site conditions are optimal for regeneration establishment. Since all of the 46 random locations (but not the baseline locations) were coincident with stands harvested between 1955 and 1975, a theoretical index was developed to express the potential influence of WSBW activity on establishment of natural regeneration in the cutover stands. This index is named "hazard index" and is defined as the product of the severity index of an outbreak and a weighting factor. Weighting factors are arbitrary multipliers that presumably represent the relative importance of the time of outbreak occurrence to the likelihood of securing natural host regeneration. If severity index is a reasonable estimate of the intensity of a WSBW outbreak, and if outbreaks of different intensity cause differential effects of the same order on regeneration, then the product of the severity index and the weighting factor of that outbreak is an index of the influence of that outbreak on the probability of securing natural host regeneration. The weighting factors for various periods of WSBW activity are:

Period of WSBW activity	Weighting factor
Entirely before cut	1
Includes 0-4 years following cut	4
Begins 5-10 years following cut	2
Begins 11 years or more following cut	1

These factors are arbitrary and are based on the following rationale: All outbreaks likely would have an adverse effect on establishment of host regeneration either because WSBW feeding weakens trees and causes long-term reduction of cone and seed crops or because direct larval feeding destroys current cones and seeds. Thus, the minimum weighting factor was set at 1 and represents activity that occurred either entirely before the cut or 11 or more years following harvest. Highest likelihood of an adverse effect would occur when an outbreak includes the period 0-4 years following the cut, during which time seeds and cones would be directly damaged by WSBW feeding and seedbed conditions for natural

[2] Seasonal precipitation is that which falls between October 1 and June 30 and is likely most influential on radial growth the following growing season.

host regeneration establishment would be best; this value was set at 4. Budworm feeding 5-10 years following harvest probably would have an intermediate effect, so this factor was defined as 2.

RESULTS AND DISCUSSION

Baseline Locations

Radial Growth and Precipitation

The hypothesis that WSBW host and nonhost trees respond similarly to local climatic variation in the absence of WSBW is supported by our data. Douglas-fir mean annual radial increment was very similar to that of ponderosa pine at stand 157 (Schwartz Creek), which had no history of WSBW, and both appear to be correlated with precipitation; growth peaks and troughs coincide with seasonal precipitation peaks and troughs (fig. 2). In the Lubrecht WSBW-infested stand 158, mean annual radial increment of ponderosa pine follows the precipitation pattern (fig. 3); however, growth of the WSBW-affected Douglas-fir diverges negatively from the pine and does not vary with precipitation. Corresponding trends (not shown) were noted for the other two stands with known WSBW history. Mean annual radial increment data for the four baseline locations are shown in table 1.

Regression of mean annual radial increment of Douglas-fir against corresponding mean annual radial increment of ponderosa pine within each of the four stands provides further support that radial increment analysis can be used to identify past WSBW activity (table 1). The coefficients of determination (r^2) between Douglas-fir and ponderosa pine at Miller Creek and Schwartz Creek were 0.40 and 0.71, respectively. Similarly, regression slopes were 1.18 and 1.09. These values are much higher than corresponding r^2 of 0.20 and 0.15 and slopes of 0.50 and -0.31 obtained at Lubrecht and Valley Creek, where past WSBW activity is known to have been high. The very low r^2 and low slope calculated for the WSBW-infested stands suggests that WSBW altered Douglas-fir radial growth. In the absence of WSBW, the near-unity slopes and higher r^2 show that Douglas-fir and ponderosa pine of similar dominance and size are also similar in radial growth pattern. This is interpreted as a normal response to precipitation and intrinsic site variables. Blais (1954) and Mott and others (1957) reached conclusions similar to ours.

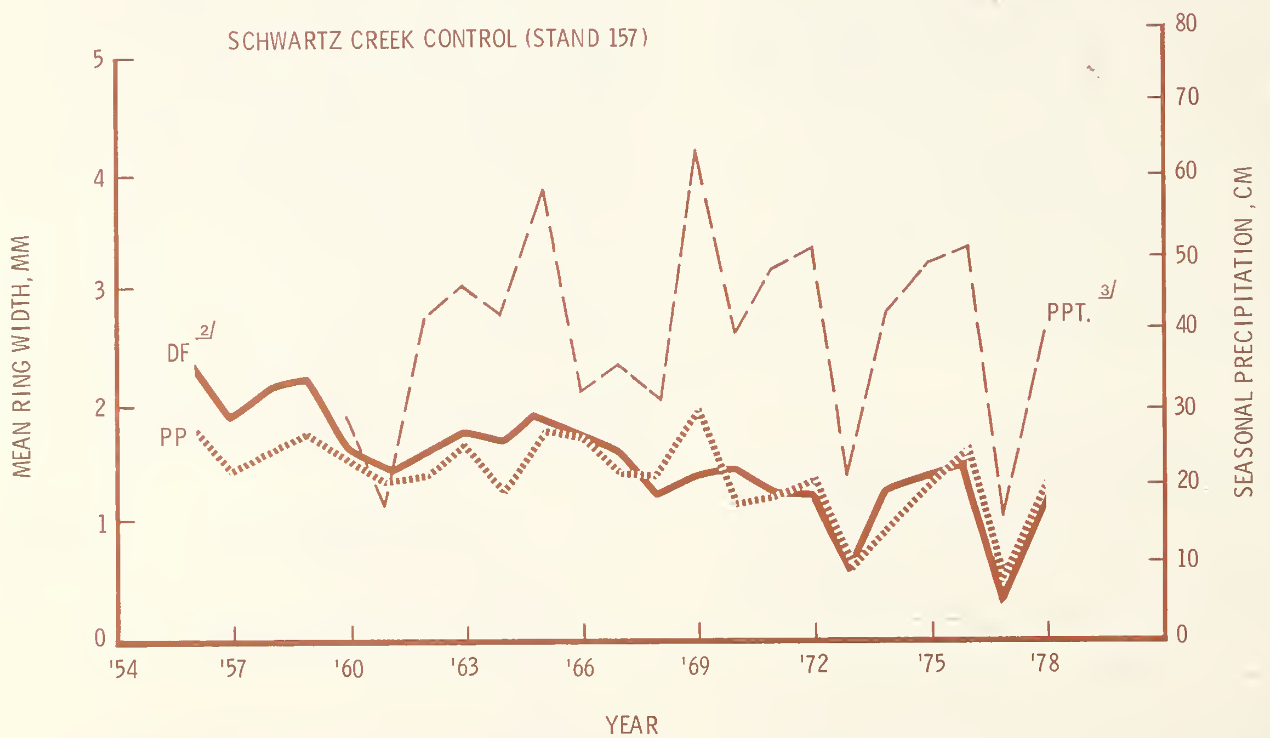

Figure 2.—Seasonal precipitation and mean annual radial increment of ponderosa pine and Douglas-fir in a stand with no history of western spruce budworm.[1]

[1] 1979 data, mean increment based on two cores from each of five trees of each species.

[2] DF = Douglas-fir, PP = ponderosa pine.

[3] PPT = seasonal precipitation that is the total precipitation between October 1 of a base year and June 30 of the following year. Data for 1956-59 were not available.

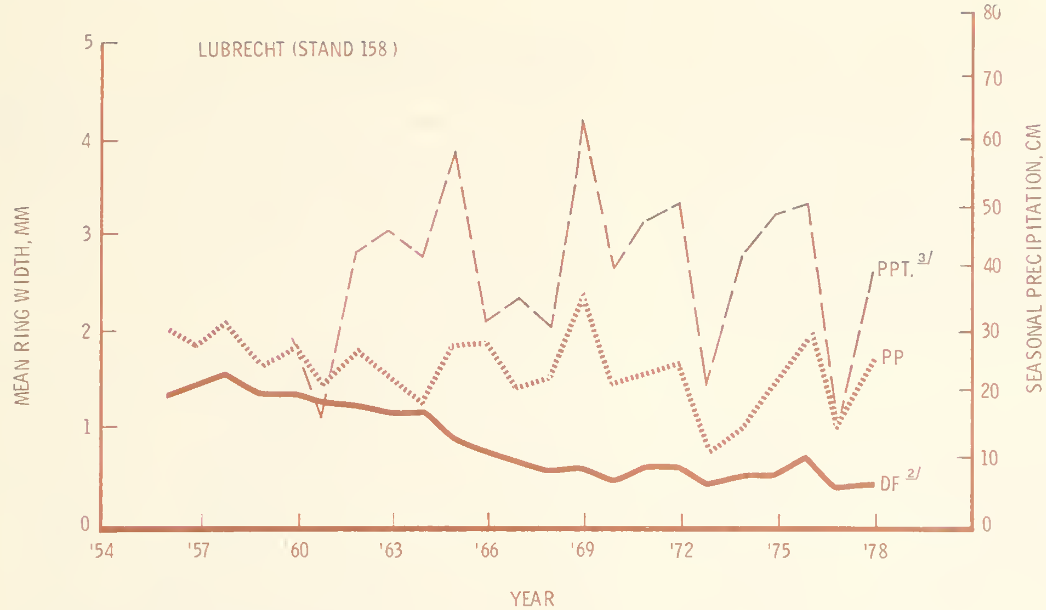

Figure 3.—Seasonal precipitation and mean annual radial increment of ponderosa pine and Douglas-fir in a stand continuously infested with western spruce budworm during 1958-79.[1]

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[1] 1979 data, mean increment based on two cores from each of five trees of each species.
[2] DF = Douglas-fir, PP = ponderosa pine.
[3] PPT = seasonal precipitation that is the total precipitation between October 1 of a base year and June 30 of the following year. Data for 1956-59 were not available.

Table 1.—Seasonal precipitation and mean annual radial increment of western spruce budworm host/nonhost trees from four locations with and without a history of western spruce budworm activity

		Mean annual radial increment							
		WSBW absent				WSBW present			
		Stand 159 Miller Creek		Stand 157 Schwartz Creek		Stand 158 Lubrecht		Stand 156 Valley Creek	
Year	PPT[1]	DF[2]	PP	DF	PP	DF	PP	DF	PP
	cm	*mm*							
1956		2.01	2.28	2.36	1.81	1.33	2.02	2.47	2.37
1957		2 10	2.13	1.92	1.49	1.44	1.85	2.48	2.53
1958		2.44	2.28	2.13	1.61	1.58	2.06	1.98	2 40
1959		2.51	2.32	2.26	1.78	1.39	1.65	1.89	2.29
1960	29.59	1.87	2.53	1.64	1.60	1.37	1.82	1.65	2.09
1961	22.12	1.83	2.41	1.44	1 31	1.23	1.44	1.38	1 93
1962	38.58	2.63	2.63	1.57	1 40	1.21	1.80	1.26	2.11
1963	41.17	3.32	2.34	1.77	1.69	1.15	1.55	1.45	1 74
1964	38.56	3.23	2.28	1.72	1 26	1 15	1.24	1.91	1.84
1965	48.54	4.04	2.42	1.91	1 73	.86	1.86	1 97	2 15
1966	31.90	3.42	2.55	1.74	1.73	76	1.89	2.33	2.32
1967	34.24	2.81	2.16	1.60	1.44	.67	1.39	2.27	1 97
1968	31.22	2 42	2.15	1.24	1 35	.53	1.50	1.88	1.66
1969	53.11	2.64	2.51	1.40	1 93	.56	2.32	1 78	1 71
1970	37.11	2.43	2.12	1.45	1.17	.44	1.41	1.51	1 54
1971	42.27	2.25	1.85	1.27	1.19	.55	1.55	1 44	1 57
1972	44.55	1.90	1.85	1.24	1 31	.55	1.62	91	1 48
1973	24.66	1.20	1.42	.58	.59	.39	71	74	1.61
1974	38.53	1.62	1.63	1.24	96	.46	1.00	54	2.25
1975	42.72	2.14	2.43	1.36	1.28	49	1.45	44	3 11
1976	43.66	2.47	2.97	1.54	1.59	.63	1.94	65	3.92
1977	20.52	.80	1.26	.35	.48	.33	1.07	85	3.70
1978	36.20	1 92	2.09	1.14	1 18	.39	1.67	.62	4.50
		Miller Creek		Schwartz Creek		Lubrecht		Valley Creek	
r^2 [3]		0.40		0.71		0.20		0.15	
Y-intercept		– .21		.00		.05		2.23	
Slope		1.18		1.09		50		– 31	

[1] Seasonal precipitation, October 1 June 30; 1956-59 data not available
[2] DF = Douglas-fir; PP = ponderosa pine
[3] Statistics for regression of Douglas-fir radial increment on ponderosa pine

Cumulative Growth Function

No important differences were observed between CGF graphs of Douglas-fir and ponderosa pine from the WSBW-free stands in Schwartz and Miller Creeks (figs. 4 and 5). However, obvious negative departures of the Douglas-fir curve relative to ponderosa pine occurred in the WSBW-infested stands at Lubrecht and Valley Creek (figs. 6 and 7). Inflections of the host curve correspond closely with the known occurrences of WSBW outbreaks in the two areas, and presumably represent the growth-retarding influence of WSBW at that time.

Severity Index

The CGF curves for stand 156 at Valley Creek indicated that two separate WSBW infestations occurred between 1956 and 1978, and that the second was the most intense (fig. 7). The severity index for the first infestation, which occurred between 1960 and 1963, inclusive, was 0.41 (table 2); the second infestation, lasting from 1969 through 1978, had a calculated severity index of 0.74. Stand 158 (Lubrecht) had one infestation active from 1960 to 1978 (fig. 6) with a severity index of 0.65 (table 2). The infestations at these two stands are known to have been acute during the last 10 years; the severity indices appear to be a sensitive measure in that they reflect that observed intensity.

Random Locations

Interpretation of CGF graphs showed that 38 of the 46 randomly selected stands had evidence of past WSBW activity (table 2); examples are shown in figures 8 and 9. It was assumed that WSBW was the only biotic factor responsible for abnormal inflections of the host growth curves, to the exclusion of needle cast fungi, root diseases, and other insects; we believe this is a valid assumption.

The cumulative growth function may be expected to differ between trees of different ages and species. We did not age our sample trees; however, this was not a problem because of the way in which CGF curves were compared within stand; we considered abrupt slope changes of host curves to be indicative of WSBW activity providing that the curve change was not observed on the nonhost graph. Also, the data showed that curves of Douglas-fir and ponderosa pine (fig. 3) were similar in stands without a WSBW history. Both species are long lived and on similar sites probably do have similar growth characteristics. The squared growth function tends to emphasize deviation from normal growth, especially in the case of prolonged growth depression. This makes the subjective interpretation of deviation from normal growth much easier; also, the squared growth function tends to be a linear transformation of a normal cumulative growth function.

Development of a regression of CGF against time may have better represented expected growth of the host rather than visual extension of the host curve; however, in many cases data were insufficient at the lower end of each curve to do that. Therefore, the visual method was judged to be the best alternative.

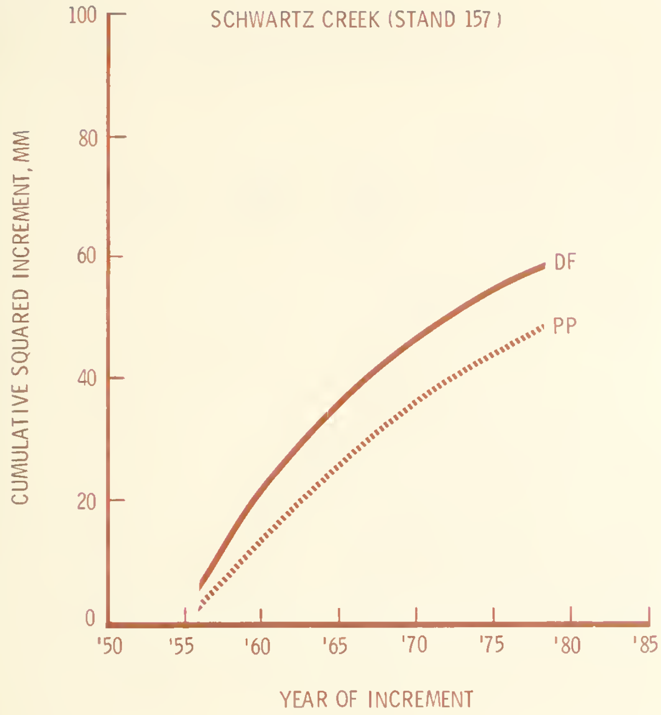

Figure 4.—Cumulative growth function for ponderosa pine and Douglas-fir at a site with no history of western spruce budworm.

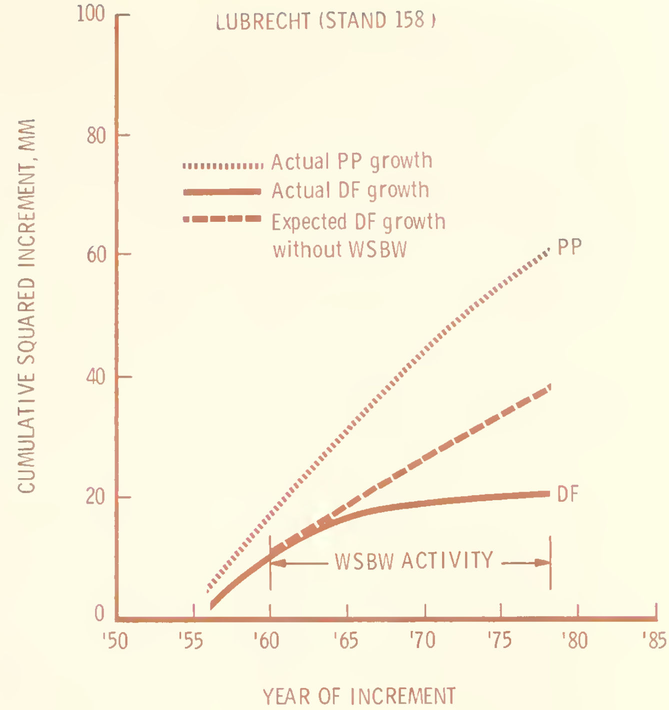

Figure 6.—Cumulative growth function for ponderosa pine and Douglas-fir at a site where western spruce budworm has been active between 1960 and 1979.

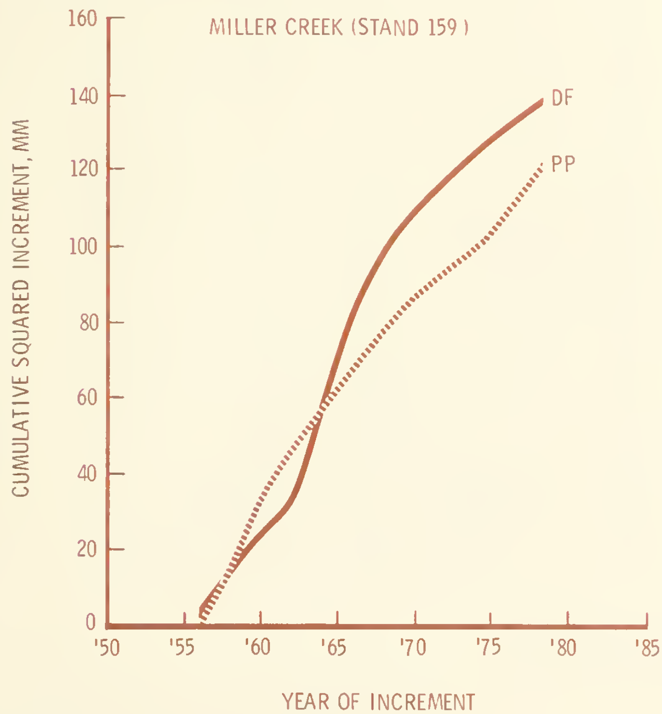

Figure 5.—Cumulative growth function for ponderosa pine and Douglas-fir at a site with no history of western spruce budworm.

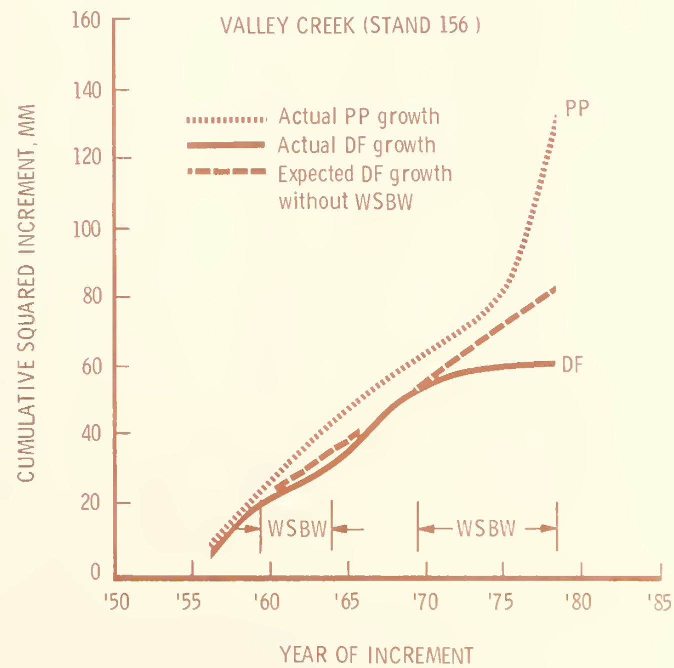

Figure 7.—Cumulative growth function for ponderosa pine and Douglas-fir at a site with two known periods of western spruce budworm activity, 1959-64 and 1969-79.

Table 2.—Western spruce budworm (WSBW) history, severity indices, and hazard indices interpreted from CGF graphs of Douglas-fir radial increment.

		Infestation start		Infestation end					
Stand number	Infestation number	Year	Actual growth (G)[1]	Year	Actual growth (T)[2]	Projected growth (P)[3]	Severity index[4]	Weighting factor[5]	Hazard index[6]
[7]157	0						0		0
[7]159	0						0		0
[7]156	1	1960	22.47	1963	28.06	32	0.41	—	—
[7]156	2	1969	52.87	1978	60.62	83	.74	—	—
[7]158	1	1960	10.28	1978	20.45	39	.65	—	—
005	0						0		0
021	0						0		0
023	0						0		0
130	0						0		0
132	0						0		0
134	0						0		0
144	0						0		0
146	0						0		0
002	1	1964	17.98	1977	25.78	39	[8] .37	4	1.48
019	1	1968	5.94	1975	10.44	14	[8] .44	4	1.76
020	1	1960	7.86	1974	13.73	28	.71	4	2.84
025	1	1958	4.71	1967	15.11	19	.27	1	.27
026	1	1972	40.48	1978	44.36	54	.71	2	1.42
031	1	1966	4.58	1974	8.91	12	.42	4	1.68
035	1	1958	3.62	1974	15.00	23	[8] .41	4	1.64
054	1	1966	2.22	1970	2.70	3	.38	1	.38
054	2	1971	2.79	1974	2.94	3	.29	4	1.16
066	1	1971	63.09	1978	68.86	87	[8] .76	2	1.52
069	1	1964	22.82	1974	26.30	40	[8] .80	4	3.20
070	1	1964	6.51	1975	10.99	13	.31	4	1.24
073	1	1958	31.05	1962	56.00	71	.38	1	.38
074	1	1958	6.25	1974	30.41	55	.50	4	2.00
100	1	1958	30.41	1963	52.35	62	.31	1	.31
102	1	1971	11.42	1978	13.49	14	.20	4	.80
124	1	1967	17.66	1974	21.89	29	[8] .63*	4	2.52
127	1	1956	2.43	1978	37.94	52	[8] .28	4	1.12
126	1	1959	33.45	1978	96.22	144	.43	4	1.72
128	1	1971	31.56	1978	33.48	45	[8] .86	4	3.44
129	1	1958	3.81	1977	11.66	24	.61	4	2.44
131	1	1958	1.82	1978	7.41	15	.58	4	2.32
133	1	1958	2.18	1978	11.42	17	.38	4	1.52
135	1	1967	4.87	1978	6.14	8	.59	4	2.36
136	1	1958	1.28	1964	2.32	4	.62	4	2.48
137	1	1965	50.21	1975	71.76	96	.53	4	2.12
138	1	1965	16.66	1974	21.35	30	.65	4	2.60
139	1	1966	22.88	1974	29.60	36	[8] .49	4	1.96
140	1	1962	4.90	1973	6.99	8	.33	4	1.32
141	1	1958	4.15	1968	9.77	21	[8] .67	1	0.67
142	1	1970	138.18	1978	150.44	188	.75	4	3.00
145	1	1958	1.99	1963	3.03	5	[8] .65	1	.65
148	1	1972	25.38	1978	27.55	32	[8] .67	4	2.68
149	1	1971	60.34	1978	64.41	74	[8] .70	2	1.40
150	1	1970	53.28	1978	61.21	71	[8] .55	4	2.20
151	1	1959	7.51	1964	17.34	24	.40	1	.40
151	2	1967	23.62	1978	32.12	44	[8] .58	4	2.32
152	1	1958	9.40	1964	20.41	24	.25	1	.25
152	2	1972	36.90	1978	41.87	46	[8] .45	2	.90
153	1	1958	3.57	1977	16.02	33	[8] .58	4	2.32
154	1	1967	62.89	1975	76.37	92	.54	1	.54
						$\bar{X}$	.51		1.67

[1] G = cumulative squared mean annual radial growth, mm, at start of infestation, computed from data.
[2] T = cumulative squared mean annual radial growth, mm, at end of infestation, computed from data.
[3] P = projected cumulative squared mean annual radial growth, mm, without WSBW, at end of infestation.
[4] Severity index $= 1 - \frac{T-G}{P-G}$

[5] Weight factor:
1 = Period of WSBW activity is entirely before date stand was harvested or begins 11 years or more following cut.
2 = Period of WSBW activity begins 5-10 years following date stand was harvested.
4 = Period of WSBW activity begins 0-4 years following harvest date of stand.

[6] Hazard index = severity index X weight factor.
[7] Baseline stand with known WSBW history. Because these areas were not associated with previous harvest cuts, weighting factors were not assigned.
[8] Radial growth of ponderosa pine accelerated in these stands during the interpreted WSBW infestation on Douglas-fir.

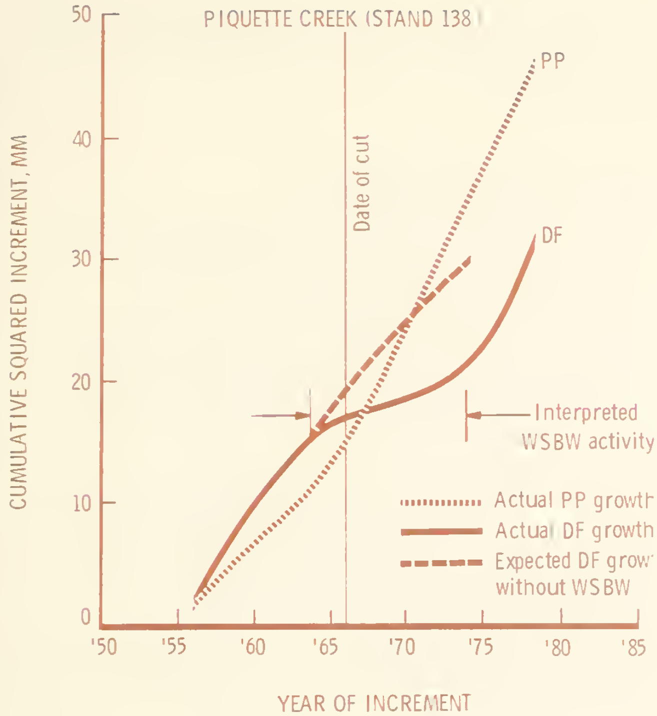

Figure 8.—Cumulative growth function for ponderosa pine and Douglas-fir and interpreted western spruce budworm activity at a site where western spruce budworm history was not known.

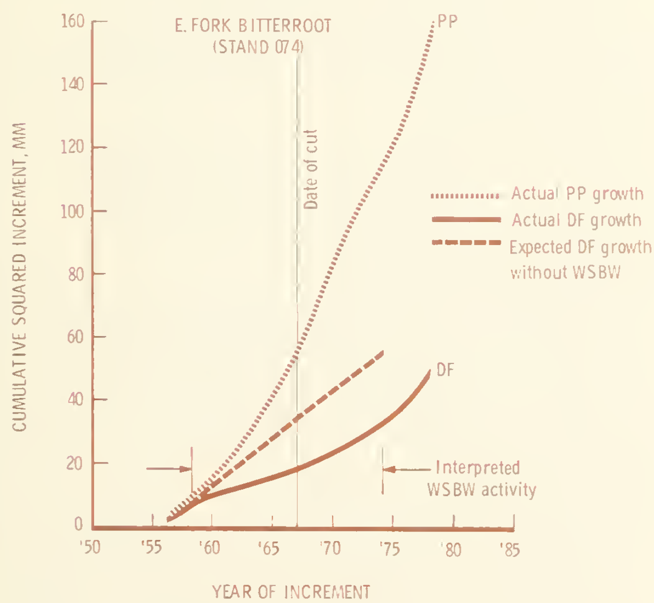

Figure 9.—Cumulative growth function for ponderosa pine and Douglas-fir and interpreted western spruce budworm activity at a site where western spruce budworm history was not known.

Severity Index

Intensity of inferred WSBW activity within the randomly sampled stands was represented by the severity index. Severity indices over the 38 stands with inferred WSBW activity ranged from 0.20 to 0.86; the mean was 0.51 (table 2). Only eight stands had no evidence of past WSBW activity, and two periods of WSBW activity were noted in three of the stands (54, 151, 152) during 1956-78.

Severity index may be useful in regression analyses of growth relationships. For example, nonhost radial growth acceleration could be quantified similar to the way it is done for host radial growth depression, and then regressed against severity index. Severity index also may be useful in multiple regression analyses of the influence of WSBW on stand structure, growth, and development over long time periods. We currently are developing working hypotheses on these concepts.

Inspection of the CGF graphs revealed that in 17 of the 38 stands with inferred WSBW history, the nonhost showed growth acceleration, presumably at the expense of the host (fig. 10). Table 2 shows that, of these 17 stands, 10 had severity indices equal to or above the mean value of 0.51. None of the pine in WSBW-free stands showed radial growth acceleration. Acceleration of nonhost radial growth in WSBW-affected stands may compensate for growth loss on host trees provided that the nonhost represents a large enough fraction of the stand.

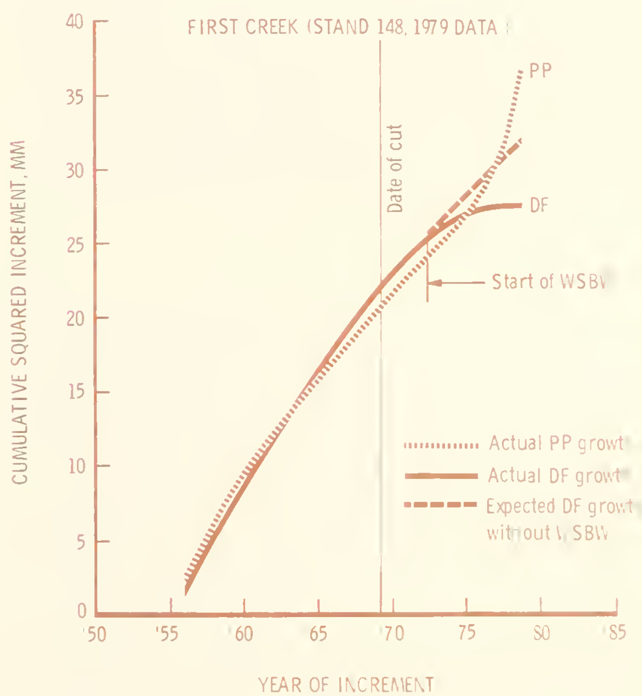

Figure 10.—Accelerated ponderosa pine radial growth during an interpreted western spruce budworm infestation.

Hazard Index

The influence of past WSBW activity on the process of regeneration establishment may be reflected in the stand WSBW hazard index. Hazard index over the 40 stands with evidence of past WSBW activity ranged from 0.25 to 3.44, with a mean of 1.67 (table 2). We currently are testing this index against probability of stocking and density of host regeneration as well as other relevant stand and site variables. Results will be reported in a future paper.

The severity and hazard indices developed from cumulative growth functions provide reasonable estimates of the occurrence and intensity of past WSBW activity. Our techniques are unique; Blais (1954, 1958, 1962, 1964) used graphic representation of actual yearly d.b.h. increment over time, and Mott and others (1957) and Williams (1966, 1967) used techniques modified from Duff and Nolan (1953) that assessed vertical, oblique, and horizontal diameter increment. Regardless of methods, all concluded that past spruce budworm outbreaks can be interpreted by tree ring analysis.

We believe that d.b.h. cores or discs are a reasonable means of collecting data to date past budworm outbreaks. However, incremental analysis of cores extracted at d.b.h. may not be the most sensitive test of past budworm activity. Mott and others (1957) and Williams (1967) presented data showing that budworm effect on diameter increment is most obvious at midcrown. Thomson and VanSickle (1980) developed a model to estimate volume losses caused by WSBW feeding. This model required data based on whole tree dissection, and they, too, found the most serious impact in the upper portions of affected trees. Nevertheless, Blais (1962) and Fritts (1976) expressed our concerns that in studies requiring rather large sample size, whole-tree dissection simply is not practical and d.b.h. cores can be used to detect previous budworm activity.

SUMMARY

This research shows that past western spruce budworm feeding activity in Douglas-fir habitat types can be detected by analysis of increment cores taken at d.b.h. A cumulative growth function, which for a given year is the sum of squared mean annual increment from a baseline year to the given year, is computed and plotted separately for WSBW host and nonhost species. Negative inflections of host curves relative to curves of nonhost likely reflect WSBW feeding. The magnitude of deflection is a measure of the severity of WSBW feeding; this is called the severity index. The severity index can be weighted to account for effects of WSBW feeding on the process of regeneration establishment following harvest of mature timber. The weighting is based on the temporal relationship of the infestation to the harvest; the weighted severity index is named hazard index.

We are just beginning to explore the use of these indices. Regression of severity index against site and stand variables may provide insight on silvicultural practices that will minimize the impact of WSBW feeding through the rotation period. Also, this technique may be useful in historical studies to document periodicity of WSBW outbreaks.

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Past western spruce budworm (WSBW) activity in western Montana Douglas-fir (*Pseudotsuga menziesii*) forests was assessed through radial increment analyses of cores extracted at diameter breast height. A growth function, defined as the cumulative sum of squared mean annual radial increment, was graphically compared between WSBW host (Douglas-fir) and nonhost (ponderosa pine [*Pinus ponderosa*]) trees. Negative inflections of host radial growth curves relative to nonhost indicated WSBW activity; these inflections were quantified and transformed to a severity index which represents the intensity of the WSBW activity. A hazard index that may reflect effects of WSBW on establishment of natural regeneration is proposed and may be suitable for analyses relating WSBW activity to regeneration probability. Acceleration of nonhost ponderosa pine radial growth during WSBW activity in mixed Douglas-fir stands was observed.

KEYWORDS: *Choristoneura occidentalis*, western spruce budworm, radial increment, western spruce budworm severity and hazard

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